PIEZO-ELECTRIC COMPRESSOR WITH DISPLACEMENT AMPLIFIER

Field of the Invention

[0001] The present invention relates to fluid compressors. In particular, this invention relates to use of a piezoelectric apparatus in fluid compressors and pumps.

Background of the Invention

[0002] Reciprocating compressors are positive displacement compressors. Positive displacement compressors take in successive volumes of a fluid which are confined within a substantially closed chamber and are forced to a higher pressure or undergoes compression. A reciprocating compressor achieves this by using a piston within a cylinder (piston cylinder assembly) as the compressing element. A fluid may be a gas or a liquid and may be both when referring to a refrigerant depending on the fluid pressure.

[0003] A reciprocating compressor uses at least two one-way valves in each cylinder that open only when a predetermined differential pressure is applied across such valves. Suction one-way valves (hereafter referred to as suction valves) open when fluid pressure in the cylinder decreases allowing a fluid to enter into the cylinder. Discharge one-way valves (hereafter referred to as discharge valves) open when at the end of the compression, fluid pressure in the cylinder increases to force the fluid out of the cylinder. This succession of suction and discharge of the fluid results in the fluid discharging at a higher pressure.

[0004] To achieve this succession of suction and discharge of fluid from the cylinder, the piston has to undergo a linear reciprocating movement in the cylinder. Referring to FIG.1, that shows a conventional reciprocating compressor, a piston cylinder assembly comprises a suction plenum 11, a discharge plenum 12, a suction

valve 13, a discharge valve 14, a cylinder 15, a cylinder bore 21 and a piston 16. Such a piston cylinder assembly is known in the art.

[0005] Linear reciprocating movement of the piston 16 for the operation of the reciprocating compressor in suction and discharge of fluid is provided by a mechanical assembly such as, for example a rotary motor assembly. The rotary motor assembly comprises a rotary motor 19, a crank 18 and a connecting rod 17. Rotation of the rotary motor 19 is translated by the crank 18 and the connecting rod 17 into a linear up/down or forward/backward movement that provides the linear reciprocating movement required in the operation of the reciprocating compressor. A downward movement of the piston 16 decreases the pressure in the cylinder bore 21 to open the suction valve 13. Consequently, the fluid is drawn into the cylinder bore 21 through the suction plenum 11. This downward movement of the piston 16 is referred to as a suction stroke.

[0006] On the other hand, an upward movement of the piston 16 compresses the fluid causing an increase in the fluid pressure, and resulting in the suction valve 13 closing and the discharge valve 14 opening. As such, the fluid is forced from the cylinder bore 21 into the discharge plenum 12. This upward movement of the piston 16 is referred to as a discharge stroke.

[0007] The above rotary motor assembly makes use of several mechanical linkages and result in many moving parts. However, such a rotary motor assembly is unnecessarily complicated and requires extensive maintenance by way of lubrication and changing of linkages. Non-in-line mechanical forces acting on the piston 16, cause excessive vibrations and noise. Furthermore, the above rotary motor assembly is prone to mechanical failure due to wear and tear.

[0008] An alternative to using a rotary motor assembly is to use a linear actuator. Linear actuators are known in the art and many of such actuators use piezoelectric elements. Generally, the piezoelectric elements in such actuators convert electrical energy into mechanical energy. In piezoelectric actuators, electrical energy is

applied to one or more piezoelectric elements to deform the piezoelectric elements and thereby physically actuate at least one other element. A limitation with existing piezoelectric actuators is that physical deformation of piezoelectric elements is relatively small. Consequently, applications using piezoelectric actuators are limited to miniature devices. Typically, displacement required in such miniature devices ranges from microns to millimeters.

[0009] To overcome the relatively small displacement of piezoelectric actuators, US Patent 5,063,542 Petermann et al. describes a displacement amplifier that interconnects a piezoelectric actuator with a displacement member. The piezoelectric actuator has bellow members that define liquid-filled expansible chambers and respond to linear displacement of piezoelectric disks to provide an amplified linear displacement to the displacement member. However, a problem with the displacement amplifier of US Patent 5,063,542 Petermann et al is that the expansible chambers are not fixed and precise control of the amplified linear displacement is therefore difficult. This concept of use of piezoelectric actuators in combination with hydraulic displacement amplifiers are further described in US Patent 5,074,654 Alden et al. and US Patent 5,697,554 Auwaerter et al. In Alden et al., a plurality of electrodistortive actuators coupled to a hydraulic displacement amplifier are used for the controlling of deformable mirrors. In Auwaerter et al., a metering valve for metering fluid for fuel injection uses a piezoelectric element coupled to a hydraulic displacement amplifier for the actuation of a valve needle to control the amount of fuel injected.

[0010] Therefore, a need clearly exists for a linear motor that applies piezoelectric elements having controllable displacement amplifiers to overcome or at least alleviate the problems of complexity, maintenance and mechanical failure in existing reciprocating compressors.

Summary of the Invention

[0011] The present invention seeks to provide a piezoelectric apparatus for use in fluid compressors and pumps.

[0012] Accordingly, in one aspect, the present invention provides a compressor having a piston cylinder assembly for successive suction and discharge of a compressible fluid, thereby increasing fluid pressure of the compressible fluid in a substantially closed chamber, wherein the piston cylinder assembly comprises a piston, a cylinder, a cylinder bore, a suction plenum having a suction valve, and a discharge plenum having a discharge valve, the compressor comprising: at least one piezoelectric element; a primary displacement member coupled to the at least one piezoelectric element; a secondary displacement member coupled to the piston; and a non-compressible fluid disposed to fill a fixed predetermined volume between the primary displacement member and the secondary displacement member; wherein electrical actuation of the at least one piezoelectric element is controllable to displace the primary displacement member by a predetermined distance, the predetermined distance being coupled via the non-compressible fluid to displace the secondary displacement member by an amplified distance based upon the fixed predetermined volume.

[0013] In another aspect, the present invention provides a compressor having a piston cylinder assembly for successive suction and discharge of a compressible fluid, thereby increasing fluid pressure of the compressible fluid in a substantially closed chamber, wherein the piston and cylinder assembly comprises a piston, a cylinder, a suction plenum having a suction valve, and a discharge plenum having a discharge valve, the compressor comprising: at least one piezoelectric element; a primary displacement member coupled to the at least one piezoelectric element; a secondary displacement member coupled to the piston; and a non-compressible fluid disposed to fill a fixed predetermined volume between the primary displacement member and the secondary displacement member; wherein, in response to electrical actuation of the at least one piezoelectric element,

displacement of the secondary displacement member is amplified relative to displacement of the primary displacement member, the displacements being based upon the fixed predetermined volume and surface areas of the primary displacement member and the secondary displacement member in contact with the non-compressible fluid.

[0014] In a further aspect, the present invention provides a fluid conveying apparatus having a piston cylinder assembly for successive suction and discharge of a fluid, wherein the piston and cylinder assembly comprises a piston, a cylinder, a suction plenum having a suction valve, and a discharge plenum having a discharge valve, the fluid conveying apparatus comprising: at least one piezoelectric element; a primary displacement member coupled to the at least one piezoelectric element; a secondary displacement member coupled to the piston; and a non-compressible fluid disposed to fill a fixed predetermined volume between the primary displacement member and the secondary displacement member; wherein, in response to electrical actuation of the at least one piezoelectric element, displacement of the secondary displacement member is amplified relative to displacement of the primary displacement member, the displacements being based upon the fixed predetermined volume and surface areas of the primary displacement member and the secondary displacement member in contact with the non-compressible fluid.

Brief Description of the Drawings

[0015] A preferred embodiment and two alternate embodiments of the present invention is more fully described, by way of example, with reference to the drawings of which:

[0016] FIG.1 illustrates a prior art reciprocating compressor;

[0017] FIG. 2 illustrates a compressor in accordance with a first alternate embodiment of the present invention;

[0018] FIG. 3 illustrates a compressor in accordance with a second alternate embodiment of the present invention; and

[0019] FIG. 4 illustrates a compressor in accordance with a preferred embodiment of the present invention.

Detailed description of the Drawings

[0020] Referring to FIG.2, a piezo-compressor 100 according to a first embodiment of the present invention is shown. The piezo-compressor 100 comprises a piston cylinder assembly similar to that of conventional reciprocating compressors as shown in FIG.1. However, instead of the conventional linear reciprocating movement supplied by a rotary motor 19, crank 18 and connecting rod 17, the present piezo-compressor 100 utilizes at least one piezoelectric element 22 coupled directly to the piston 16.

[0021] When actuating electrical signals are supplied to the piezoelectric element 22, the piezoelectric element 22 is deformed to displace the piston 16 linearly by a predetermined distance upward (discharge stroke). This increases the fluid pressure in the cylinder bore 21 and opens the discharge valve 14 to discharge the compressible fluid from the cylinder bore 21 into the discharge plenum 12. The subsequent actuating electrical signals electrically actuate the piezoelectric element 22 to deform in a manner that displaces the piston 16 linearly downward by a predetermined distance (suction stroke). This lowers the fluid pressure in the cylinder bore 21 and opens the suction valve 13 thereby drawing the compressible fluid from the suction plenum 11 into the cylinder bore 21.

[0022] The actuating electrical signals supplied to the piezoelectric element 22 are typically in accordance with specifications governing use of the piezoelectric element 22. Such actuating electrical signals comprise a series of voltage or

current pulses of a predetermined amplitude for actuating of the piezoelectric element 22.

[0023] When such actuating electrical signals are supplied to the piezoelectric element 22 continuously, the piezoelectric element 22 is electrically actuated to reciprocally deform in a respective direction to execute either the suction stroke or the discharge stroke. This linear reciprocating movement of the piezoelectric element thus also causes the piston 16 to undergo the required linear reciprocating movement for the operation of the piezo-compressor 100. The operation of the piston cylinder assembly in the piezo-compressor 100 is similar to that of conventional reciprocating compressors. However, the piezo-compressor 100 advantageously has less moving parts and is less prone to mechanical failure. Such piezo-compressors could be advantageously utilized as mini or micro compressors for use in applications requiring continuous and constant dynamic operations while undergoing invariant loadings. Invariably, such piezo-compressors could also be advantageously utilized as fluid conveying apparatuses such as pumps. When used in applications as pumps, the fluid conveyed may be both compressible or non-compressible.

[0024] Referring to FIG.3, an improved piezo-compressor 200 according to a second embodiment of the present invention is shown. In addition to utilizing at least one piezoelectric element 22, a displacement amplifying means such as a spring 32 is added. Typical linear displacement achieved by piezoelectric elements are in the range of microns to millimeters. In certain applications, such small displacements do not constitute sufficient reciprocating linear movement to operate a piezo-compressor 100 at a high enough capacity. The spring 32 acts as a displacement amplifier that translates the linear reciprocating movement of the piezoelectric element 22 into an amplified linear reciprocating movement. Consequently, the linear reciprocating movement of the piston 16 is also amplified, thus increasing the volume of compressible fluid handled at each suction or discharge stroke thereby increasing the capacity of the piezo-compressor 200. However, the amplified linear reciprocating movement provided by such a spring

32 may not be well controlled and may develop harmonics which may eventually act against the linear reciprocating movement of the piezoelectric element 22. There is also dependency on the inherent mechanical spring constant of the spring 32, which may deteriorate with constant use.

[0025] Referring to FIG.4, a super piezo-compressor 300 according to a third embodiment of the present invention is shown. In addition to a desirability for having larger linear reciprocating movement of the piston 16, there is also a desirability for better control over the linear reciprocating movement of the piston 16. The super piezo-compressor 300 achieves this by utilizing a hydraulic displacement amplifier. The hydraulic displacement amplifier comprises a primary displacement member 46 coupled to the piezoelectric element 22, a secondary displacement member 44 coupled to the piston 16, a non-compressible fluid 45 disposed to fill a fixed predetermined volume between the primary displacement member 46 and the secondary displacement member 44. The non-compressible fluid 45 thus couples the primary displacement member 46 to the secondary displacement member 44. An example of such a non-compressible fluid 45 would be a hydraulic oil or a compressor lubricating oil. The secondary displacement member 44 is further coupled to the piston 16 by way of a piston rod 42. The surface area of the primary displacement member 46 in contact with the non-compressible fluid 45 is typically larger than that of the surface area of the secondary displacement member 44 in contact with the non-compressible fluid 45.

[0026] When actuating electrical signals are supplied to the piezoelectric element 22, the piezoelectric element 22 deforms and displaces the primary displacement member 46 by a small predetermined distance. However, the secondary displacement member 44 is displaced by an amplified predetermined distance through coupling with the non-compressible fluid 45 and thus also causes the piston 16 to be displaced by an amplified predetermined displacement via the piston rod 42. Amplification of displacement of the secondary displacement member is based upon the fixed predetermined volume and dimensions/surface

area of said primary displacement member and said secondary displacement member.

[0027] The relationship between the amplified displacement and the surface areas of the primary displacement member 46, the predetermined distance displaced by the primary displacement member 46 and the secondary displacement member 44 may be shown below:

[0028] $L = \frac{A}{a} \times l$

[0029] Where L is the amplified displacement displaced by the secondary displacement member 44 and l is the predetermined distance displaced by the primary displacement member 46. Where A is the surface area of the primary displacement member 46 in contact with the non-compressible fluid 45 and a is the surface area of the secondary displacement member in contact with the non-compressible fluid 45.

[0030] A stopper 47 can further be coupled to a piston spring 43 which is further coupled to the secondary displacement member 44. The stopper 47, together with the piston spring 43 serves to assist in the linear reciprocating movement of the secondary displacement member 44. Consequently, this also assists in the linear reciprocating movement of the piston 16.

[0031] The hydraulic displacement amplifier does not merely provide for amplification of the linear displacement of the piezoelectric element 22. The hydraulic displacement amplifier also provides for better control of the linear reciprocating movement of the piston 16.

[0032] The piezo-compressors 100, 200, 300 described in FIG.2, FIG.3 and FIG.4 have been depicted and described in a vertical layout. They have also been described singularly. However, it would be obvious to a person skilled in the art to

operate the described piezo-compressors 100, 200, 300 in other orientations without departing from the scope of the invention. Further, that the piezo-compressors could also be used in plurality, in a variety of arrangements, and in applications other than compressors and pumps, without departing from the scope of the invention. It will be appreciated that various modifications and improvements can be made by a person skilled in the art without departing from the scope of the present invention.